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The challenges for energy efficient casting processes

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Abstract

Casting is one of the oldest, most challenging and energy intensive manufacturing processes. A typical modern casting process contains six different stages, which are classified as melting, alloying, moulding, pouring, solidification and finishing respectively. At each stage, high level and precision of process control is required. The energy efficiency of casting process can be improved by using novel alterations, such as the Constrained Rapid Induction Melting Single Shot Up-casting process. Within the present study the energy consumption of casting processes is analyzed and areas were great savings can be achieved are discussed. Lean thinking is used to identify waste and to analyse the energy saving potential for casting industry.

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Keywords: Energy efficiency; casting; Value Stream Mapping

1. Introduction

Energy saving and reducing emissions are primary goals of all countries around the world. Increase in world population and scarcity of energy resources and dramatic increase in pollution have lead towards energy saving by more efficient use of fuels such as coal, oil, gas and where possible use of renewable energies.

Energy consumption by different sectors has been investigated thoroughly and reported in numerous reports [1]. Indicatively, manufacturing accounts for 32% of the total energy consumption [2]. According to the Climate Change Agreement published by UK Government [3], the foundries sector in the UK needs to attain an energy burden target of 25.7 GJ/tonne. However, the average energy burden for the UK foundry sector is 55 GJ/tonne. Therefore saving energy in foundries by increasing efficiency in production line can help to save millions of pounds for manufacturing sector and reduce emission.

Casting is one of the oldest metal forming processes, relying in pouring the melt metal into a desired shaped mould and wait until it solidifies. It is often used to manufacture complex parts, which are too expensive or time consuming to produce by other methods. However, casting probably is one of the most challenging manufacturing process. It is a highly technical engineering process requiring deep scientific understanding. A typical modern casting process contains six different stages, namely melting, alloying, moulding, pouring, solidification and finishing respectively. At each stage, high level and precision of process control is required. Casting process also is one of the most energy intensive manufacturing processes. The metal melting consumes over half of the energy in a casting process. Therefore, the expenses on the casting process has been a significant concern due to the rising of the energy prices.

2. Potentials for energy savings

The energy intensity of a process has a positive relation with the share of the energy cost in the total variable costs and of the value of the product [4]. The more energy intense a process is, the greater the cost of the process. As a result of these pressures, industrial energy saving is becoming increasingly important from the aspect of the economy. A number of research studies have been carried out for identifying opportunities for energy saving. Generally, energy saving can be achieved through several techniques and methods. In a number of studies, the authors have employed energy audits for coming up with suggestions for energy savings. Energy audits have been used

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in a number of different sectors, indicatively Klugman et al. performed an energy audit at a chemical wood pulp mill in Sweden [5] and came up with suggestions such as updating existing equipment to reduce energy consumption by 50%. Salonitis proposed an energy audit strategy for identifying the energy consumption of the various components of a manufacturing process [6].

However, audit methods only provide theoretical figures about energy saving and often simply suggest major equipment updates. This kind of energy efficiency management often requires significant capital investment on new equipment. Comparing energy saving and capital investment, Anderson pointed out that plants are 40% more responsive to initial cost rather than annual saving [7]. With regards to new equipment and the adoption of new technology for long-term savings, organisations prefer projects with shorter payback times, lower costs and greater annual saving. Therefore, it is not surprising that Thollander's research indicates that about half of the foundries in Sweden lack a long-term energy strategy and only about 25% may be categorised as having a successful energy management practice [8].

There are several barriers that prevent a company from becoming energy efficient [2],[8]. The main barriers identified are technical risks, such as the risk/cost/hassle/inconvenience of production disruptions, inappropriate technology for the operation, lack of time and priorities, lack of access to capital and slim organisation. In particular, for SME foundries, the lack of time, proper personnel and insufficient resources are the largest barriers to energy efficiency [9].

Instead of direct energy saving through big investments in new technology and equipment, a lean philosophy can be introduced to eliminate waste, improve quality and eventually, achieve the goal of energy saving. The concept behind lean manufacturing is simple; it is to spot and eliminate waste in a production process rather than inspect and repair afterwards. In the lean philosophy, the word 'waste' can be rather complicated. It can represent a machine breakdown, product defects and physical waste during the production process. Most importantly, it represents those resources or processes that do not create products or services directly. By implementing lean tools such as Just in Time (JIT), cellular manufacturing, value stream mapping (VSM), waste caused by machine breakdowns, product defects, physical waste and non-value added processes could be reduced or eliminated. The consequence of such an implementation reduces the production resource requirements, costs and lead-time, while increasing the product quality, customer responsiveness and boosting competitiveness. However, lean tools are implemented less in continuous manufacturing sectors such as the foundry sector. This is because of the large stocks of input raw materials and the long setup times that are required and the general difficulty in producing small batches [10], [11], Abdulmalek and Rajgopal undertook research on the steel foundry and investigated which lean tools could be implemented [10]. The summary of his work is shown in Table 1.

Table 1. Assessment of applicability of lean tools in the steel industry.

Lean tool	Applicability
Cellular manufacturing	Probably inapplicable
5S	Partially applicable
Setup reduction	Universally applicable
Value stream mapping (VSM)	Universally applicable
Just in Time	Partially applicable
Production levelling	Partially applicable
Total productive maintenance	Partially applicable
Visual System	Universally applicable

Few studies have been reported on the use of lean techniques for foundries. Indicatively, Girishi et al. utilized VSM for the entire production flow of the casting process and identified the waste during each operational step [12]. It was discovered that with minimum interventions, the foundry could reduce waste by 23%, which corresponds to significant energy savings. Kukla proved that the implementation of Total Productive Maintenance in a casting industry will allow for efficient management of machinery and increase its effectiveness, resulting in improved production flow and lower production costs [13]. However, even fewer studies attempt to link the elimination of waste with the practice of energy saving in casting industry. Therefore, this work uses lean thinking to identify waste and to analyse the energy saving potential for casting industry.

3. Methods for saving energy

By adopting concepts such as VSM, the entire operation of the casting process can be investigated. Energy savings can be achieved in two ways: direct savings through lower fuel consumption and indirect savings through lower material consumption. Therefore, for energy savings in the foundry; less fuel and less material should be used for producing a certain quantity of sound products. To accomplish this, an understanding of the flows of energy and materials in the casting process is required. Figure 1 presents the process flow for conventional casting. This can be divided into six sub-processes: melting, refining, holding, fettling, machining and inspection. The melting, refining and holding activities consume most of the energy involved in casting (at least 60%); thus, the direct energy savings should be achieved in this step. Fettling, machining, and scrap contain at least 70% metal by weight of the total melting [14]; thus, the indirect saving should come from these three processes.

4. Quantifying potential savings: direct savings

4.1. Savings through preheating the metal and loading

The first step of the melting process is the preheating of the metal. There are several advantages related to preheating: it can remove moisture and other organics, which helps preventing explosion in the furnace; it can increase the melting capacity of the furnace; and it can reduce the energy required for melting. Especially for aluminium alloy, preheating can inhibit slag formation when the hot aluminium comes into contact with moisture [15].

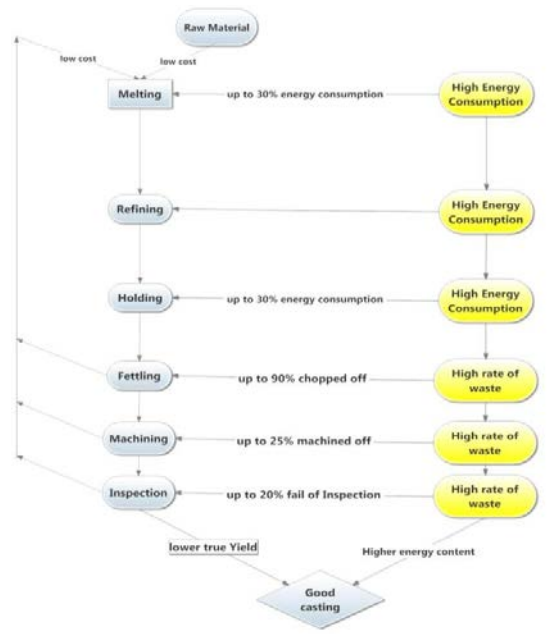

Fig. 1. Material and energy flow chart of a conventional sand casting process.

Nowadays, foundries often use hot flue gases from the melting furnace to preheat the metal. Mefferta investigated how much energy could be saved by preheating in the iron foundry sector [16]. Using recovered exhaust gases should be seen as the primary method of reheating. However, loading or transferring the preheated metal may cause the loss of vast amounts of heat through convection and radiation. Therefore, reducing the energy lost during transportation can retain significant amounts of energy and reduce the energy required by melting. To achieve this efficiently, the pre-heating and melting operations should be close to each other and a lean tool such as 5S could be employed (tidy up work floor to reduce the time of movement).

4.2. Savings through melting

The melting of the metal phase consumes 30% of the energy of the casting process. Thus, saving energy through the melting operation logically becomes a primary consideration. When considering energy saving via the melting operation, the efficiency of the furnace is of paramount importance. If the efficiency of the furnace increases, the energy consumed per unit mass of metal reduces.

Table 2 presents several popular furnace types used in the aluminium foundry industry. Clearly, the induction furnace is the most efficient melting method compared with the other two furnace types. However, 60% of the energy currently used in melting is provided by natural gas and only 27% of the melting is provided by electricity [17].

Table 2. Capacity, fuel type and energy efficiency of different furnaces [17].

	Melt capacity	Fuel Type	Efficiency
Crucible Furnace	Several kg to tone	Natural gas / coal / oil	7 – 19%
Reverberatory furnace	1 t to 75,000 t	Natural gas / coal / oil	20 – 25%
Induction furnace	Several kg to 30 t	Induction	85 – 97%

Therefore, this raises another debate between energy saving and cost saving. Using a gas-fired furnace can save money but the quality of the melt is poor. The quality of the melting influences the subsequent sub-processes. Hydrogen content is normally higher in gas-fired furnaces owing to the moisture-rich exhaust gases. Removing hydrogen is essential because it causes serious damage later on. Therefore, compared with material melted by using electrical means, using gas requires additional treatment in degassing. Therefore, although less money are spend during the melting, the process requires additional expense during degassing.

Irrespective of the purpose for cost or energy savings, some recommendations are introduced for the improvement of energy efficiency.

1. Improving the air compressor that controls the fuel-fired furnace [16]. Oxygen enrichment can lead to higher heat transfer rates and thus, reduce melting times. In turn, this would reduce the overall fuel consumption [17].
2. Reducing the frequency of metal charging [18]. This can reduce the metal loss and the radiation heat loss. Metal loss refers to losses through oxidation when in contact with air. Radiation loss refers to heat losses when the furnace lid or door is opened [17].
3. When considering lean manufacturing, it is recommended to use high-quality raw material. Using high-quality raw material may increase the initial cost. However, in return, it can reduce overall metal losses through oxidation and drossing. Lowering the metal loss requires less energy and metal to compensate.
4. Providing training for the furnace operators. It has already been shown that operator performance can influence energy usage by as much as 10%.

Further to increasing energy efficiency, there is also an alternative ways for engineering energy savings. For example other strands of lean manufacturing can be used such as the use of correctly sized equipment to produce the desired amount of products. For the aluminium sector, it is recommended to use the correct size and a rapid-melting coreless induction furnace for the melting. The advantages of such a furnace can be summarized into:

1. High-efficiency furnace saves energy during melting
2. Cleaner energy leads to cleaner metal, lower hydrogen content and less need for other treatments
3. The correct size furnace can ensure no waste during casting; it can smooth the casting process and no residual liquid needs to be held

Fast melting reduces the chance of oxidation; thus, reducing the need for additional metal to compensate the metal loss

4.3. Savings through treating and refining molten metal

Following the melting operation, the molten metal usually includes impurities, such as oxides and slag and undesired gas content such as hydrogen. As a result, degassing and flotation are necessary requirements. Normally, the hydrogen in aluminium comes from the decomposition of water vapour. Following the reaction, hydrogen gas dissociates and forms hydrogen atoms, which diffuse into the melt 0. As the aluminium solidifies, the dissolved hydrogen escapes from the melt to form undesirable porosity, unfurl DOFs, or even form cracks. Therefore, reducing the hydrogen content is essential during the degassing operation. Nowadays, the technology used for degassing is purging with an inert gas via a rapidly rotating nozzle 0. This technology is based on the equilibrium relationship between the hydrogen in the melt and the hydrogen in the atmosphere. By injecting the inert gas, the molten metal is put under an inert atmosphere. To maintain the balance, hydrogen needs to transfer into the inert gas bubble and diffuse to the surface of the melt. As the purging of the melt by the inert gas continues, the hydrogen content gradually drops to the required level. According to literature [14], the metal loss during the treating and refining operations can be as high as 5% in terms of mass. Assuming a melt of 1 tonne of aluminium uses 2.2 GJ of energy. The loss of 5% of the metal requires an additional 0.11 GJ of energy to melt. Energy is also consumed by the degassing unit; the rotating motor, the inert gassing and the flux pumping all require energy. A mid-range degassing unit is usually powered by a 3.5 KW motor for period of 15 minutes. Therefore, the energy consumed is 3.15 MJ. Furthermore, the embedded energy required to compress the inert gas into the container also needs to be considered. Assuming the purging rate of the inert gas is 20 L⊕min-1, which gives 300 L of gas in total, the embedded energy of the inert gas would be about 0.5 MJ [14]. Combined with the consumption by the motor, the total energy consumption could be 3.65 MJ.

In order to save energy through refining and treating, the quality of the raw metal is very important. It not only reduces metal loss during refining but also reduces the frequency of refining. In addition, there are the corresponding savings of inert gas and electricity to be considered as well.

4.4. Savings through holding

Holding is another significant consumer of energy in the casting process, demanding another 30% of the energy of the casting production. The purpose of holding is to maintain a continuous supply of liquid for casting with constant composition and quality [17].

Owing to its characteristics, the holding furnace can operate as long as a working shift (8 hours). In most non-ferrous foundries, the holding process requires more energy than the melting process does. Reducing the holding time is one of the most efficient ways for energy saving. To achieve this, a smooth and continuous production plan is essential. Lean tools, such as TPM, VSM, production levelling and planning can be used to assess the holding time reduction.

5. Quantifying potential savings: indirect savings

5.1. Savings through operational material efficiency improvement

Operational material efficiency (OME) is the ratio between the good casting shipped to customer and the total metal melted [14]. Improving the true yield is probably the simplest way in which foundries can save energy, because this method focuses on increasing good casting production and reducing the total metal melted. It deals mainly with the production process itself, seeking opportunities to save material. It has less relation with the performance of the production equipment. To be able to understand the true yield of the casting process, the entire casting operation needs to be analysed. Using a traditional sand casting as an example, the casting process is analysed briefly in the following.

Aluminium is a highly reactive material. In particular, when it is liquefied at high temperature, it can react with air, moisture, the furnace lining and other metals. The metal loss during the melting process is due mainly to this characteristic. As discussed before, a casting process can be divided into seven sub-processes: melting, holding, refining, pouring, fettling, machining and inspection. Apart from pouring, six out of seven have a direct relation with metal loss, table 3.

Table 3. General metal loss during each operation. Data based on general / automotive sand casting production [14].

	Melt-ing	Holding	Refin-ing	Fettling	Machin-ing	Inspe-ction
Metal loss	2%	2%	5%	50%	25%	20%

Figure 2 presents the metal flow during conventional sand casting process. By assuming 1 kg of metal is melted, then after the different stages of the operation, the final casting dispatched to customer only weighs about 0.27 kg. Therefore, the operational material efficiency of this casting process is about 27%. For conventional casting, 1 Kg of good casting requires 3.7 Kg of raw materials. Therefore, if the true yield of the casting can be improved, less metal will be required to produce the casting and the energy consumption for the melting could be reduced.

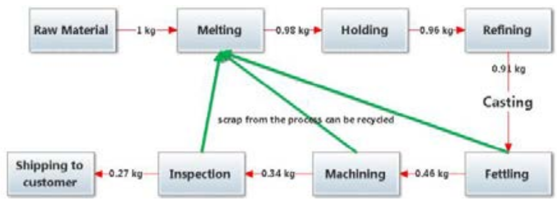

Fig. 2. Metal flow in the foundry.

Opportunities to improve the true yield require that the metal loss during each operation must be reduced. Starting with the melting operation, 2% of the metal loss is mainly due to the oxidation of the aluminium at the surface of the melt. Thus, keeping the melt away from contact with air can reduce the level of oxidation. Normally, this can be done by keeping the lid of the furnace shut and reducing the metal charge time. Secondly, the holding process also contributes 2% of the loss, which can also be attributed to oxidation (long term exposure). Therefore, reducing the holding time can reduce the metal loss. Thirdly, the refining / cleaning operation contributes 5% of the metal loss. The loss at this stage of the operation is due mainly to oxidation, hydrogen degassing and impurities. The rate of the loss depends on the cleanliness of the raw material. Thus, good quality raw material is essential.

After pouring, solidification and shakeout, the casting system is sent to the fettling operation. Fettling is used to separate the casting and its running system. Generally, the casting itself is only about 50% by weight of the entire casting system. Therefore at least half of the metal is chopped off and scrapped. This is the principal cause of metal loss during the casting process. For foundries producing aerospace castings, the metal loss during fettling can be as high as 90% owing to the strict quality regulations [14]. Thus, reducing the weight of the running system can reduce the metal loss in fettling. The concept of a good casting running system will be introduced later.

The fifth cause of losses relates to machining. This process transforms the casting into its final shape. It involves grinding, drilling, boring, turning, polishing and any other necessary operations. The metal loss during this stage of the operation is mainly in the form of fine scrap. If the casting can be produced closer to net shape, then the need for machining operations can be reduced. The final type of loss is that of castings that fail the inspection process. Defects such as a poor tolerance, poor surface finish, inclusions and porosity lead to rejection during the inspection. To reduce the level of rejections, the processes of melting, alloying and refining and the design of the running system are very important.

The losses in first three steps are permanent losses, which cannot be easily recovered or reused. They can only be reduced by the methods mentioned. The last three types of loss are assigned as internal scrap. Energy has been used to make and melt this metal and because these losses can contribute up to 90% of the metal loss in the casting process, energy savings must be achieved by reducing such losses during the casting process.

5.2. Savings through using numerical simulation

Starting from the product design, the behaviour of the fluid inside the casting running system and the performance of the feeder during solidification can be predicted by using a numerical simulation package. This allows foundry engineers to develop sound products without doing physical experiments of trial and error. This can help at both initial production and during long runs when an energy saving method is being sought.

5.3. Savings through plant management

A typical foundry consumes 14% of its energy on air compression, which costs even more money than melting or holding (Figure 3). There are many reasons for using compressed air in a foundry; the most important is for combustion. Generally, compressed air can provide more oxygen for combustion. Efficient burning of fuels can provide a hotter flame temperature, which gives a higher heat transfer rate and reduces the time required for melting [17]. Furthermore, it not only reduces the heat loss during combustion but also reduces the environmental impact. Again, there are always two sides to everything. Compressed air helps reducing the fuel consumption during combustion but it consumes significant quantities of electricity. Therefore, ensuring that there is no excess air in the burner will help greatly in reducing the need for compressed air. Furthermore, using the correct size of compressor and routine maintenance can also save energy. Ultimately, using an induction furnace will eliminate the requirement for compressed air and lean tool such as TPM can be extremely helpful for this purpose.

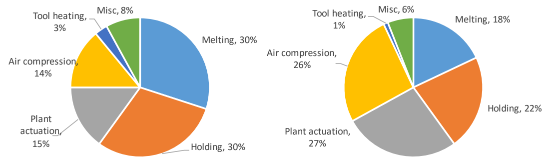

Fig. 3. (a) Typical energy use and (b) typical energy cost in a foundry.

6. Saving energy through CRIMPSON process

Constrained Rapid Induction Melting Single Shot Up-casting (CRIMSON), was developed recently [14] for improving the energy efficiency of a casting process. The process uses a rapid induction furnace to melt just enough metal for one single casting; then transfer the molten charge to a computer controlled counter gravity casting platform. The highly controlled metal flow is pushed into the mould to finish the pouring and solidification. Such process reduces the defect generation and energy consumption by rapid melting, minimum holding and smooth filling of the mould.

Table 4. Summary of energy loss and opportunities for energy saving during each operation.

	Energy loss reason	Saving method	Saving type
Melting	1. Inefficient melting 2.Permanent metal loss	1. Correct size of furnace 2. Rapid melting 3. Keep melt away from air	Direct / Indirect
Refining	Permanent metal loss	1. Using high-quality charging metal 2. Cleaning melting	Indirect
Holding	1. Long-term holding 2.Permanent metal loss	Reducing the holding time	Direct / Indirect
Fettling	Low casting yield	Increasing the casting yield	Indirect
Machining	Rough shape of casting	Making net shape casting	Indirect
Inspection	Defects such as inclusion, poor surface finish, porosity	1. High-quality melting 2. Good running system	Indirect

Direct and indirect methods of saving energy during the casting process have been introduced. At the starting point of the casting process, using the correct size of rapid induction furnace with matched billet size for high subsection not only saves energy during melting but can also reduce metal loss as well; both direct and indirect savings can be achieved. Refining is the second step in the casting process and savings during this stage rely mainly on loss reductions. This requires good quality charging materials and clean melting. Savings during the holding process can be achieved both directly and indirectly. Reducing the time of the holding can reduce energy consumption and metal loss. Savings achieved during the fettling, machining and inspection stages of the process are all indirect savings. All of these processes achieve savings by increasing the casting yield. Simulation methods can be used to achieve casting yield improvements. Therefore, a good running system with high casting yield not only guarantees the quality of the casting but also saves energy.

Based on these concepts, the CRIMSON casting process combines direct and indirect saving methods; thus, achieving energy savings in a more efficient way. The energy and material flow diagram of the CRIMSON process is shown in figure 4.

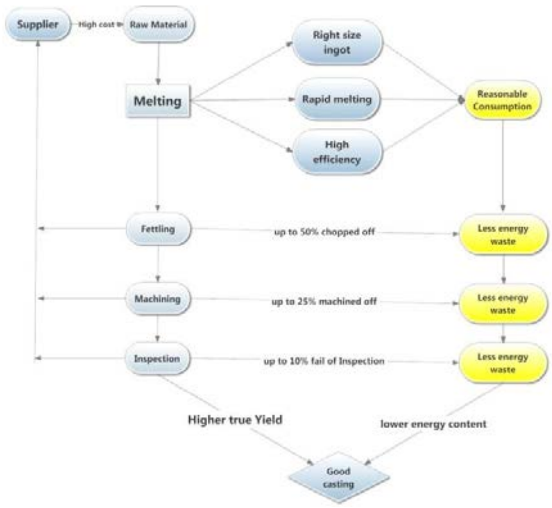

Fig. 4. Material and energy flow chart of the CRIMSON casting process

Instead of using cheap bulk metal, the CRIMSON process uses pre-alloyed high-quality metal for the casting process. Moreover, the CRIMSON casting process uses a rapid induction furnace to melt just enough metal for a single casting. The time for melting is normally under 10 minutes, which reduces significantly the chance of the oxidation and hydrogen absorption. Therefore, the refining stage of the operation is no longer necessary. Because of the single melting, the melt can be transfer to the pouring operation immediately; thus, the holding operation can be also removed from the casting process. Considering that the holding process can consume up to 30% of the casting energy, eliminating this stage can plug a significant drain of energy consumption. Owing to the new filling feature of the CRIMSON process, the liquid metal is pushed into the casting system through a bottom gate. This up-casting method redefines the casting running system and the pouring basin and down-sprue are no longer required. Because of the new running system, less metal is fed into the running system and thus, the casting yield increases.

With regard to quality, the up-casting process provides a turbulence-free filling, which means that defects, such as air entrapment and DOF formation can be minimised. The quality of the casting can be improved to a new level and fewer rejections reduce the energy consumed by re-working.

7. Conclusions

In the present paper the challenges for optimizing the casting processes with regards their energy efficiency were discussed. CRIMSON process as an alternative was presented, and shown that it has advantages compared to conventional sand casting process. It can result in better casting quality due to great filling rate control; it saves energy through holding free casting production and high OME; under the CRIMSON capacity, it has higher productivity compared with the conventional sand casting process; most importantly, it costs less to produce same casting products compared with the conventional sand casting process. The next steps of the present work will be on melting various ferrous and non-ferrous alloys by CRIMSON, to be able to use this method for mass production.

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